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A review of maximum power point tracking techniques of PV system for uniform insolation and partial shading condition

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A B S T R A C T

This paper presents a review on the state-of-the-art maximum power point tracking (MPPT) techniques for PV power system applications. The main techniques that will be deliberated are the Perturb and Observe, Incremental Conductance and Hill Climbing. The coverage will also encompass their variations and adaptive forms. In addition, the more recent MPPT approaches using soft computing methods such as Fuzzy Logic Control, Artificial Neural Network and Evolutionary Algorithms are included. Whilst the paper provides as thorough treatment of MPPT at normal (uniform) insolation, its focus will be on the applications of the abovementioned techniques during partial shading conditions. It is envisaged that this review work will be a source of valuable information for PV professionals to keep abreast with the latest progress in this area, as well as for new researchers to get started on MPPT.

Contents

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1. Introduction

Despite the relatively high cost of solar modules, PV power systems have been commercialized in many countries for its long term economic prospects and more crucially, the concerns over the environment [1]. These systems, which could be grid-connected or stand-alone, are being installed in wide-ranging power capacities and by using various silicon technologies. Regardless of the type and size, one critical component of any PV is the effectiveness of its maximum power point tracker (MPPT). This area has been and is still attracting immense interest from PV research communities as well as industrial players because it is the most economical way to improve the overall PV system efficiency.

Conceptually, MPPT is a simple problem—it is basically an operating point matching between the PV array and power converter. However, because of the non-linear *I–V* characteristics of the PV curve and the consequence of the varying environmental conditions (particularly insolation and temperature), tracking the correct maximum power point (MPP) can sometimes be a challenging task. The tracking becomes more complicated when the entire PV array does not receive uniform insolation—a condition known as partial shading [2]. This issue has received much attention lately, partly due to the proliferations of building-integrated (BIPV) in urban areas. The BIPV, which is commonly installed on rooftop, often lends itself to shading because of unfavourable physical constraints such as space limitations and unforeseen structural development. Notwithstanding, partial shading is also being experienced in large PVPS installations, i.e., solar farms. Typically, it is caused by the clouds that strike on certain spots of the solar array, while other parts are left uniformly irradiated. Such meteorological condition is quite common in tropical and near-equatorial regions. Another source of partial shading-like characteristics is exhibited by module irregularities; a common example would be the presence of cracks on one or more modules of the PV array.

When a PV system is subjected to partial shading, its *P–V* curves exhibit multiple peaks with several local peaks and a unique global peak (GP). The conventional MPPT algorithm, such as Perturb and Observe, Hill Climbing and Incremental Conductance (to name a few) is likely to be trapped at one of the local peak, simply because its algorithm could not differentiate the local with the GP. Consequently, it oscillates around the vicinity of the local peak and remains there indefinitely—a significant reduction in the PV power yield will be experienced [3].

Over the years, numerous MPPT techniques have been proposed; this is evident from the growth in number of related papers published in various journals and proceedings [4,5]. Despite the fact that these methods are designed for the same objectives, they differ markedly in terms of complexity, convergence speed, steady state oscillations, cost, effectiveness and flexibility. Furthermore, numerous researches have been carried out to address the partial shading effect by improvising the conventional MPPT controllers. However, with recent availability of vast and low cost computing power, new methods based on soft computing techniques have been attracting considerable interests. This approach, which includes the Fuzzy Logic Controller, Artificial Neural Network and Evolutional Algorithm, offers numerous opportunities for more robust and flexible MPPT schemes, in a way that is not possible using conventional techniques. More importantly, these methods are well suited to cater for the partial shading conditions.

In a short span of time, the body of knowledge related to this subject has grown tremendously. Clearly, it is difficult to keep track with the literatures unless a single reference with concise and accurate summaries of the various MPPT schemes is made available. The most recent reviews [4,5] are carried out over five years ago, and obviously progress since then has been considerable. Therefore, it seems appropriate at this juncture to provide a comprehensive and up to date review of the subject. In particular, the MPPT for partial shading conditions is not fully documented; justifiably, there is a critical need to carry out this exercise even more.

Although this paper will mainly deal with the latest work on MPPT, it is envisaged that some background knowledge would be helpful for certain group of readers to follow through this paper effectively. Accordingly, information on the principles of operation, limitations and advantages of the conventional MPPT methods (and their variations) are provided. However, since the number of papers related to one particular method is quite large, it is imperative that only works with significant contributions are cited. Papers that refer to previous works with minor modifications or improvements may not be included in the reference list. In that regard, apologies are offered to the respective authors.

2. MPPT control structure with power converters

The aim of employing MPPT is to ensure that at any environmental condition (particularly solar insolation and temperature), maximum power is extracted from the PV modules. This is achieved by matching the PV's MPP with the corresponding power converter's operating voltage and current. Fig. 1 shows the general block diagram of MPPT in conjunction with a dc–dc converter. Although a stand-alone dc–dc system is depicted here, the application can be extended to a grid connected PV system by adding other power electronic devices such as inverter and grid components. Basically, the MPPT works by sensing the current and voltage of the PV array; using this information the array power is calculated and compared with the present value of MPP. Accordingly, the duty cycle of the converter is adjusted using a PI or hysteresis controller to match the MPP—which in turn, forces the converter to extract the maximum power from the array.

An alternative control structure is characterized by directly updating the duty cycle of the power converter; this is known in

literature as the direct duty cycle MPPT control. In this scheme, the PI block in Fig. 1 is eliminated and duty cycle is computed directly in the MPPT algorithm. This scheme offers number of advantages: (1) it simplifies the tracking structure, (2) it reduces the computation time and (3) no tuning effort is needed for the PI gains. In short, it replaces the sophisticated MPPT control with a more simplified structure while maintaining similar optimal results.

3. Partial shading condition

Fig. 2 shows a PV array in a typical series-parallel configuration. In this example, the modules are connected in strings, with three modules per string. When one of the modules in the string experiences less illumination due to shading, its voltage drops; thus it behaves as a load instead of a generator. A hot spot ensued and typically a bypass diode is connected in parallel with each PV module to protect the shaded module from being damaged. Additionally, a blocking diode is connected at the end of each string (combination of series modules in one current path) to provide the protection against reverse current caused by the voltage mismatch between the parallel-connected strings.

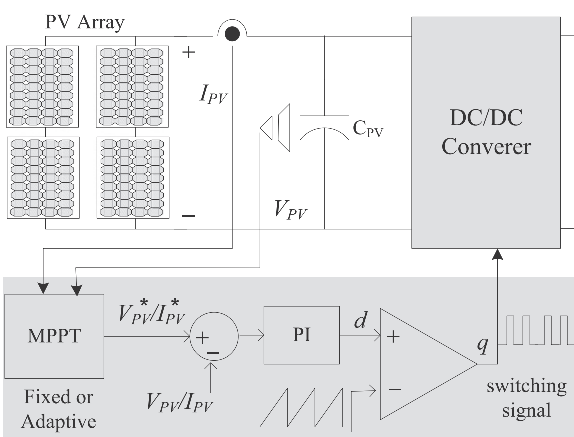

Fig. 1. A typical voltage or current based MPPT system.

In normal condition, i.e., when the solar insolation on the entire PV array is uniform, as shown in Fig. 2(a), the *P–V* curve exhibits the typical unique MPP (curve 1 of Fig. 2(c)). During partial shading, as the third PV module being less illuminated (shown by shaded block in Fig. 2(b)), the difference in insolation between two modules activates the bypass diode of module 3. As a result, two stairs current waveform is created on the *I–V* curve. Consequently, the corresponding *P–V* curve is characterized by several local peaks and one global peak (GP), as depicted by curve 2. Furthermore, if the bypass diode is removed, the PV array exhibits only a single peak (curve 3); but this is achieved at the expense of a significant reduction in power. Therefore, in general, the bypass diode is always installed to improve the power throughput of the PV array, despite the complication that arises during partial shading [6].

4. Categorization of MPPT techniques

In this paper, the selected MPPT are systematically categorized into two main groups. First, which is by far the most popular, is referred to as the conventional MPPT. Three main methods (together with their important variations), namely the Perturb and Observe (P&O), Incremental Conductance (IC) and the Hill Climbing (HC), will be discussed in detail. The other group is based on soft computing techniques. They are becoming more important lately due to the availability of vast and cheap computing power. The techniques that fall into this category include the Fuzzy Logic Controller (FLC), Artificial Neural Network (ANN) and Evolutionary Algorithms (EA). The last, in particular, is of interests due to its natural suitability to adapt for multi-modal problem imposed by the partial shading condition. They shall be discussed comprehensively in this paper.

Besides these, there are other MPPT described in literature: Fractional Short Circuit Current (FSC) [7–10], Fractional Open Circuit Voltage (FOV) [11–14] and Ripple Correlation Control (RCC) [15–19]. These MPPTs have limited accuracy but they do have their own distinct advantages, namely fewer sensors and simpler algorithm; thus they offer a reliable and lower cost solution for certain applications. Other techniques include current sweep method [20], DC-link capacitor drop control [21,22], load current and load voltage minimization [23–27], *dP/dV* or *dP/dI*

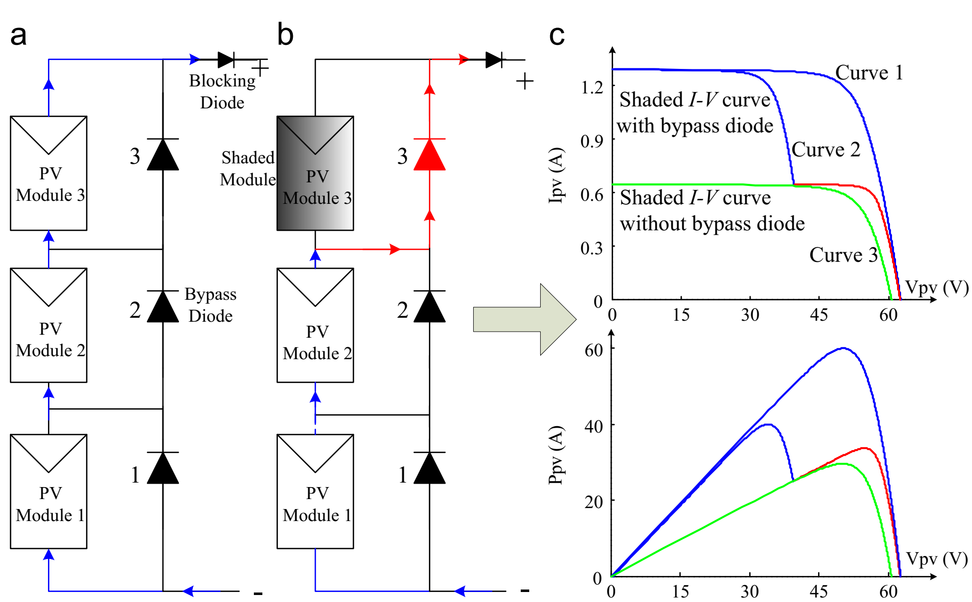

Fig. 2. Operation of PV array (a) under uniform insolation (b) under partial shading (c) the resulting *I–V* and *P–V* curve for (a) and (b).

feedback control [28–32], linear current control [33], state based MPPT [34], best fixed voltage algorithm [35], linear reoriented coordinate method [36] and slide control method [37]. They are not as popular and hence have been omitted for brevity.

5. Conventional MPPT under uniform insolation

5.1. Perturb and observe (P & O)

5.1.1. Principle of operation

The working principle of P&O is depicted by the flowchart in Fig. 3. The algorithm introduces a perturbation (Φ) in the operating voltage and current of PV array and subsequently the change in the operating power is observed. The increment in operating power implies that the converter is getting closer to the MPP. Accordingly, in the next sampling cycle, the direction (slope) of perturbation is retained and the reference voltage/current is further increased by an amount Φ. Note that once the vicinity of MPP is reached, with each new perturbation (which is changed in sign alternately), the algorithm will go back and forth around the MPP. Consequently, it will never stick exactly at MPP; rather, it oscillates around that point indefinitely.

5.1.2. Previous important work on P&O

Since Φ can be constant or variable, two types of P&O are reported in the literature, i.e., the fixed step and adaptive, respectively. For the fixed step P&O, authors in [38] proposed a two-stage grid connected inverter; the first stage is comprised of a two-switch buck-boost converter that performs the MPPT and sinusoidal waveform generation. Hashimoto et al. [39] proposed a novel MPPT control algorithm for a half bridge inverter with a control unit consisting of a multistage buck-boost converter. The proposed MPPT enables each of the PV modules to generate its maximum power by simply detecting only the total output power of the PV system. Authors in [40] exploit the capability of multi-objective optimization technique to design the one-cycle controller for single-stage inverter. The optimization technique is the basis to design the P&O based method. In another work [41], using a simple auxiliary resonant circuit, an MPPT for soft-switching boost converter is proposed. To track the MPP under rapid changes in insolation, authors in [42] propose a three-point weight comparison P&O method. The slope of the Φ is decided based on the comparison of the actual operating power to two preceding ones. Other efforts to solve this issue are carried out by exploiting the sampling rate of MPPT. For instance, the sampling rate is optimized in [43], while authors in [44], simply use a high sampling rate.

Work in [45] suggests an adaptive P&O scheme for a grid-connected three-phase inverter. In the beginning, the Φ is set to be 10% of the V_{OC}. Each successive perturbation is set to 50% of the preceding one until the value of Φ is 0.5% of the V_{OC}. Although the method exhibits somewhat better performance, it is still not fully adaptive due to the predetermined perturbation steps. Patel and Agarwal [46] proposed a threshold-based MPPT scheme for single-stage grid-connected PV system. The system operates in the continuous conduction mode and employs only voltage sensor. The array current is estimated using the inductor current.

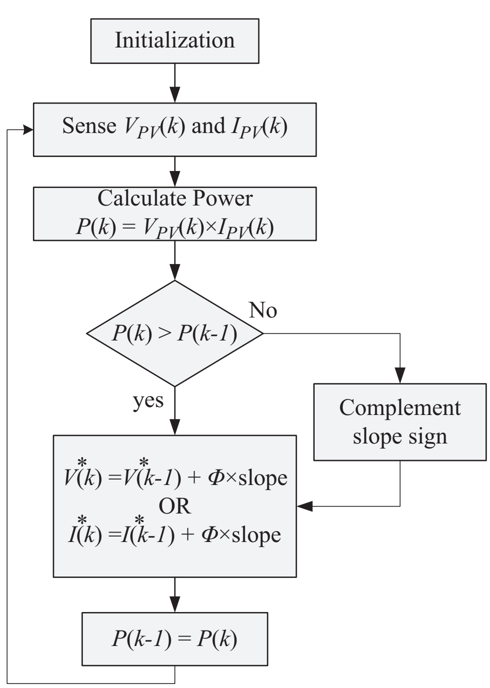

Fig. 3. Flow chart of conventional Perturb and Observe (P&O) method.

5.2. Incremental conductance (IC)

5.2.1. Principle of operation

The idea behind IC is to incrementally compare the ratio of derivative of conductance with the instantaneous conductance [47]. It is derived from the fact that at MPP, the derivative of power with respect to voltage (dP/dV) is in fact zero, i.e.,

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0 \tag{1}$$

Eq. (1) can be rearranged in the following form:

$$-\frac{I}{V} = \frac{dI}{dV} \cong \frac{\Delta I}{\Delta V} \tag{2}$$

where ΔI and ΔV are the increments of PV current and voltage, respectively. The basic rules for IC can thus be derived from the P–V characteristics shown in Fig. 4 and can be written as:

$$\begin{cases} \frac{dI}{dV} = -\frac{I}{V}, & \text{At MPP} \\ \frac{dI}{dV} > -\frac{I}{V}, & \text{Left of MPP} \\ \frac{dI}{dV} < -\frac{I}{V}, & \text{Right of MPP} \end{cases} \tag{3}$$

Using the rules in (3), the basic flow chart for IC is depicted in Fig. 5. It can be noticed that the reference signal is based on voltage, V^*. Since the rules in (3) are derived using P–V curve, the current cannot be used as the final output. Instead, the P–I characteristics curve is utilised. To use IC as a current based

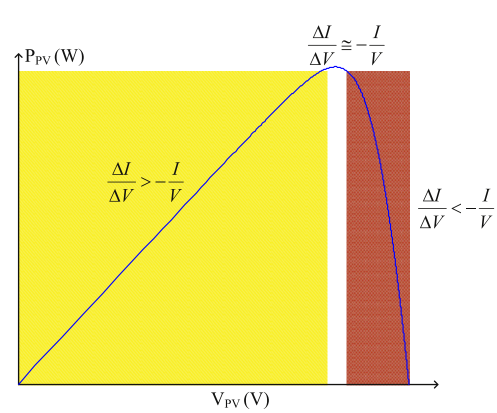

Fig. 4. P–V characteristics for the basis of IC method.

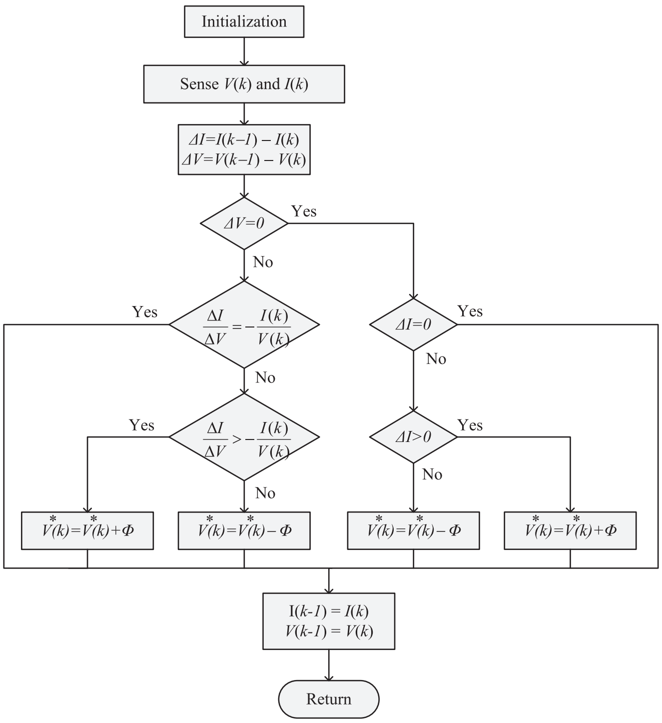

Fig. 5. The basic flow chart of the voltage based IC method.

MPPT, Eq. (1) can be modified as:

$$\frac{dP}{dI}=\frac{d(VI)}{dI}=V+I\frac{dV}{dI}=0 \tag{4}$$

Accordingly, the rules in (3) will be transformed to

$$\begin{cases} \frac{dV}{dI}=-\frac{V}{I}, & \text{At MPP} \\ \frac{dV}{dI}>-\frac{V}{I}, & \text{Left of MPP} \\ \frac{dV}{dI}<-\frac{V}{I}, & \text{Right of MPP} \end{cases} \tag{5}$$

Using (5), the flow chart in Fig. 5 can be transformed into current based IC by interchanging V with I, ΔV with ΔI and $V(k)^*$ with $I(k)^*$. Subsequently, the method will be characterized by incremental resistance (*IR*), not IC.

5.2.2. Previous work on IC

Considering its superior dynamic performance, many authors [48–53] employ IC in its original form. For instance, in [48] an interface circuit using IC for solar cells without battery storage is proposed. In two separate works [49,50], the IC method is applied to track the MPP in a single-stage grid inverter system using a two-mode scheme. If the insolation is sufficient, it operates in solar generation mode, otherwise in active power line conditioning mode. In [51], a hybrid approach is proposed to track the MPP of the module-integrated converter. The authors utilize a linear function to segmentize the *I–V* curves into MPPs and non-MPPs region.

Another effective way to utilize the IC is to generate an error, ε, using the instantaneous conductance and the incremental conductance [52]. Mathematically, it can be written as:

$$\frac{dI}{dV}+\frac{I}{V}=\varepsilon \tag{6}$$

From (6), it can be seen that the value of ε is zero at MPP. The value of ε is usually selected based on the trade-off between the accuracy of (3) and the allowable oscillations around MPP. Considering the advantages of (6), authors in [52] introduce marginal error ε in (3), i.e., $(dI/dV+I/V)<\varepsilon$. Furthermore, in [53], a totally different approach is proposed; IC is implemented using the mixed-signal circuit. A major portion of the MPPT algorithm is realized using analog circuits which exploit the linear region of a field-effect transistor.

For adaptive IC, numerous works have been reported [54–57]. For instance, Mei et al. [54] suggest an improved *IR* method, where two modes of perturbation step are used, i.e., fixed and variable. In another work related to adaptive IC, Li and Wang [55], vary the value of Φ in original IC method with respect to dP/dV using the following equality

$$\Phi=N\left|\frac{P(k)-P(k-1)}{V(k)-V(k-1)}\right| \tag{7}$$

In (7), N is the scaling factor, which is tuned using a trial and error method. Authors in [56] propose a three-phase grid-connected PV system with modified IC method and reactive power compensation. Similar to [55], a threshold value, based on the change in solar insolation, is used to adjust Φ. In the case of increasing insolation i.e., ΔP is positive, Φ is selected to be smaller and consequently a smooth tracking towards MPP is achieved. By investigating the characteristics of PV array in the voltage and current source region, authors in [57] propose another type of adaptive IC. If $r=V(k)/I(k)$ and $r_s=dV(k)/dI(k)$, then (8) outlines the basic idea of their method, i.e.,

$$\begin{cases} -\infty<r/r_s<-1, & \text{Voltagesourceregion} \\ r/r_s=-1, & \text{At MPP} \\ -1<r/r_s<0, & \text{Currentsourceregion} \end{cases} \tag{8}$$

Using (8), the reference value of the MPPT algorithm is expressed by:

$$r_{ref}(k+1)=r_{ref}(k)+Mu_r \tag{9}$$

$$\mathrm{M}=1+r/r_s \tag{10}$$

where r_{ref} is a reference value of a constant resistance and u_r is a unity conversion factor for the resistance domain.

5.3. Hill climbing (HC)

5.3.1. Operation of HC

In principle, the HC operation is very similar to P&O; the only difference is, instead of perturbing the voltage or current, it updates the operating point of the PV array by perturbing the duty cycle, $d(k)$ by a fixed step-size (Φ) in the direction of increasing power. The perturbation direction is reversed if $P(k)<P(k-1)$; an indication that the tracking is not moving towards the MPP. This can be described by the following equation:

$$d(k)=\begin{cases} d(k)+\Phi, & \text{if } P(k)>P(k-1) \\ d(k)-\Phi, & \text{if } P(k)<P(k-1) \end{cases} \tag{11}$$

Due to the fact that the duty cycle is changed directly without a PI controller, the HC method is sometimes known as the direct duty cycle technique. As with the case of P&O, this method can be characterized by fixed or adaptive perturbation step.

5.3.2. Previous work on HC

Considering the fact that the parallel capacitance connected at the output affects the characteristics of the PV array, Kasa et al. [58] estimate Φ by the following equation:

$$\Phi=K_M\times C_{PV}\times\frac{1}{\hat{C}_{PV}(k)} \tag{12}$$

where $\hat{C}_{PV}(k)$ is the estimated value of capacitance C_{PV}. It is reported that the power from the PV array can be transferred to

the utility grid with the nearly unity power factor at the maximum power point. Koutroulis et al. [59] use HC for buck converter battery charging PV system, while in [60], the authors simplify it for a fly back inverter using only voltage sensor. Jain and Agarwal [61] apply the conventional HC scheme on a high gain inverter, operating in discontinuous current mode. This allows for the low PV array voltages (typically 50–100 V range) to be boosted up to the level of grid voltage (115 V or 230 V ac systems). In another work [62], HC is used in a parallel connected MPPT system for stand-alone PV power generation. The proposed structure reduces the negative influence of dc–dc converter losses, hence increasing the efficiency of power generation. Kwon et al. [63] propose a simple three-level boosting MPPT control for a three phase grid connected PV system. The proposed MPPT converter, which utilizes the HC algorithm, reduces the reverse recovery losses of the diodes and thereby increases the overall efficiency.

Chiang et al. [64] propose a modification to (12) to formulate an adaptive HC algorithm. The perturbation step Φ is computed using the following relationship:

$$\Phi = \frac{\Delta P/\Delta d}{P/d} \tag{13}$$

In a separate work, Xiao and Dunford [65] exploit the *P–D* curve for the PV array. Using the value of (dP/dD), they tuned the perturbation value Φ using

$$\Phi(k) = M\frac{\Delta P}{\Phi(k-1)} \tag{14}$$

If the change in array power (ΔP) is large due to rapid environmental variations, $\Phi(k)$ is forced likewise to ensure improved dynamic performance. When ΔP is small, the system is near to MPP and accordingly, the value of $\Phi(k)$ will also be small. Wolfs and Tang [66] propose another modification to (14) using the relation of dP/dV as follows:

$$\Phi = M\frac{\Delta P}{\Delta V} \tag{15}$$

However, since the value of M in (15) primarily decides the performance of MPPT, manual tuning of this scaling factor can be extremely sensitive to initial operating conditions. To overcome this issues, Pandey et al. [67] propose a fully adaptive HC method to automatically tune M under all operating conditions. This is calculated using

$$M = \frac{|\Delta V_{MAX}|\Delta D_{MAX}}{|\Delta P_{MAX}|} \tag{16}$$

where, ΔV_{MAX} and ΔP_{MAX} are the maximum change in array voltage and power, respectively, with respect to maximum change in duty cycle ΔD_{MAX}.

As the HC method works on the same principle like P&O, its dynamic performance suffers similar problem to the latter, i.e., the divergence of MPP. The three point sampling technique [42] can also be applied in HC to overcome this problem.

5.4. IC with direct duty cycle

Another class of direct duty cycle control is inspired by the IC method. The duty cycle of the converter is varied according to the rules given in (3). Like other techniques, this method can also be employed in its original form or adaptive. Xuesong et al. [68] utilize the IC algorithm depicted by the flowchart in Fig. 5. Despite the absence of PI control loop, it is shown through simulations that this method can satisfactorily track the MPP. Using the same concept of marginal error ε as reported in [52], Safari and Saad [69] use a Cuk converter as the MPPT converter. Although fast and accurate, the method is not generic because for different PV system, the perturbation step Φ and marginal error ε need to be recomputed based on trial and error approach.

Various adaptive IC are proposed to obtain the best trade-off between MPP oscillations and dynamic performance. In [70], based on a threshold value of operating power ε, a two step based direct duty cycle IC method is proposed. Small value of Φ is used in the vicinity of the MPP while big step is used in other regions. Using the same idea of [67], Liu et al. [71] propose another auto tuning scheme for the scaling factor M in (17). The value of M is constrained to the following inequality:

$$M < \Delta D_{\text{MAX}} \Big/ \left|\frac{dP}{dV}\right|_{\text{Fixed Step} = \Delta D_{\text{MAX}}} \tag{17}$$

If (17) is not satisfied, the algorithm works with a fixed step size. Additionally, for smooth start, a simple start program is introduced to the MPPT method. Another work carried out by [72] presents an alternative form of adaptive IC; Φ is calculated using

$$\Phi = \pm M\left|\frac{\Delta I}{\Delta V} + \frac{I(k)}{V(k)}\right| = \pm Cf(k) \tag{18}$$

As duty cycle always fall in a particular range, M is allowed to be selected from the following inequalities:

$$\frac{\Delta D_{\text{MIN}}}{f_{\text{MAX}}(k)} < M < \frac{\Delta D_{\text{MAX}}}{f_{\text{MAX}}(k)} \tag{19}$$

where

$$f_{\text{MAX}} = \left|\frac{\Delta I}{\Delta V} + \frac{I(1)}{V(1)}\right| \tag{20}$$

6. Soft computing MPPT under uniform insolation

6.1. Fuzzy logic control (FLC)

6.1.1. Operation

In FLC, a mathematical model of the system is not required. This in itself is a significant advantage because the uncertainties such as un-modelled physical quantities, non-linearity and unpredictable changes in operating point can be excellently dealt with [73,74]. However, it does require the designer to have some prior knowledge of how the output responds qualitatively to the inputs. The typical process structure of an FLC is shown in Fig. 6. The controller has three functional blocks namely fuzzification, rules inferences and defuzzification. In addition, it has a rule table in which the designed rules are stored. The process in which the FLC performs the calculation is called rule inference.

The inputs to a FLC-based MPPT are usually an error E and a change in error ΔE. Since dP/dV vanishes at the MPP, both inputs can be calculated as follows:

$$E(k) = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \quad \text{or} \quad E(k) = \frac{P(k)-P(k-1)}{I(k)-I(k-1)} \tag{21}$$

$$\Delta E = E(k) - E(k-1) \tag{22}$$

Once E and ΔE are computed and converted to the linguistic variables, the FLC output can also be defined linguistically in terms of voltage (ΔV), current (ΔI) or duty cycle (ΔD). The

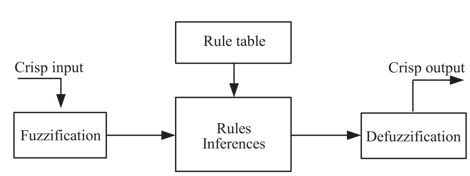

Fig. 6. Fuzzy logic control (FLC) process structure.

linguistic variables for the output signal are usually assigned based on innate knowledge of the particular PV system being employed.

6.1.2. Previous work using FLC

In [75], an FLC with seven linguistic variables is used, while in [76] and [77], the membership functions are made less symmetric to give more significance to the specific linguistic variables. In an effort to overcome tracking deterioration with respect to changes in solar insolation experienced by [78], authors in [79] introduce the array power variation and duty cycle as the inputs for the FLC. Although, it performs satisfactorily in varying environmental conditions, it could not reduce the steady state error in the array power. Extending the idea of [78] and [79], authors in [80] propose a 3-input FLC based MPPT. The information derived from array current, power and duty cycle of converter are selected as the inputs to the FLC. Some improvements are seen in [81], where the authors employ the Fuzzy Cognitive Networks (FCN) to enhance the performance of [78]. The voltage, current, temperature, solar insolation and control variable (current) are used as the nodes of the FCN. The weights of the interconnection nodes are determined using a wide range of different climatic conditions. Once the FCN is trained, it can be mounted on any PV system. The proposed method results in better tracking speed, but at the expense of additional switch and a sensor.

In [82], the authors exploit the advantages of the FLC to improve the performance of the conventional HC method. The FLC is developed by translating the HC algorithm into 16 fuzzy rules. In addition, several authors utilise the idea of adaptive FLC. For instance, in [83], an adaptive FLC is proposed to facilitate the constant tuning of the membership functions and the rule based table in order to achieve optimum performance. In another work, [84], the scaling factor of both fuzzy inputs and output are automatically tuned to achieve the better dynamic performance of MPPT.

Authors in [85] propose a single input fuzzy logic controller (SI-FLC) by applying the "signed distance method" [86]. The input to SI-FLC consists of only one variable known as "distance". This is in contrast to the conventional FLC, which requires an error and the derivative (change) of the error as its inputs. The reduction in the number of inputs simplifies the rule table to one-dimensional, allowing it to be treated as a single-input single-output controller.

6.2. Artificial neural network (ANN)

6.2.1. ANN operation

The ability of ANN to recognize and estimate unknown parameters inspired its application for MPP tracking [87]. The input variables to the ANN can be PV array parameters such as V_{OC} and I_{SC}, insolation and temperature, or any combination of these. The output is usually a reference signal, which can be either the voltage, current or duty cycle. To accurately identify the MPP, the weights associated to the neurons have to be carefully computed through a comprehensive training process. Once trained, the ANN can be used as the MPP estimator which will give the reference value (V_{MP} or I_{MP}) to the MPPT controller.

6.2.2. Previous work

Typically, the ANN is used to estimate the MPP with respect to environmental variations. For example, in [88], the ANN is utilized to identify the MPP using a gradient descent algorithm training. Other authors used the capability of ANN to improve the P&O or IC method; Alabedin et al. [89] develop an ANN based P&O controller. Compared to the FLC based MPPT, the proposed method results in improved performance in dealing with the fluctuations in the array power. Authors in [90] propose a novel

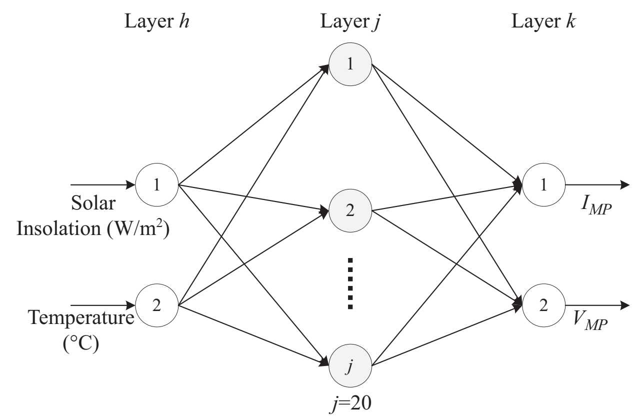

Fig. 7. The ANN structure for [90].

ANN technique, as shown in Fig. 9, to further improve the P&O performance. It can be seen that the insolation and temperature are used as the input for the network together with 20 neurons in the hidden layer. In another work, [91], the authors improve the conventional IC method by combining it with a trained ANN.

Most ANN methods [88–91] employ back-propagation (BP) training algorithm. Larger number of hidden nodes yield more accurate results, but at the expense of longer computational time. Hence, in rapid fluctuations of environment, the ANN MPPT may not be able to respond quickly enough to cope with the fast changes. Moreover, the BP algorithm remembers the new value but forgets the old, leading to the poor memory retainement. Therefore, in general, ANN is unsuitable for low cost microprocessors Fig. 7.

6.3. Evolutionary algorithm (EA)

Another soft computing approach that is gaining attention recently is the evolutionary algorithm (EA). It is a stochastic method that appears to be very efficient in optimizing real-valued non-linear and multi-modal objective functions [92,93]. Since the technique is based on search optimization, in principle, it should be able to locate the MPP regardless of environmental variations. Various EA methods for MPPT are found in the literature; the most popular ones are Particle Swarm Optimization (PSO) [94], Genetic Algorithm (GA) and Differential Evolution (DE)

6.3.1. PSO

PSO is a population-based search method, modelled after the behaviour of bird flocks [95]. The algorithm maintains a swarm of individuals (called particles), where each particle represents a candidate solution. Particles follow a simple behaviour: emulate the success of neighbouring particles, and achieve their own successes. The position of a particle is therefore influenced by the best particle in a neighbourhood, as well as the best solution found by the particle. Particles positions, $\boldsymbol{x}_i$, are adjusted using:

$$x_i^{k+1} = x_i^{k} + v_i^{k+1} \tag{23}$$

Note that in (23) where the velocity component, v_i, represents the step size. The velocity is calculated by:

$$v_i^{k+1} = wv_i^{k} + c_1 r_1 \{P_{best\ i} - x_i^k\} + c_2 r_2 \{G_{best} - x_i^k\} \tag{24}$$

where w is the inertia weight, c_1 and c_2 are the acceleration coefficients, r_1, $r_2 \in U(0,\ 1)$, P_{besti} is the personal best position of particle i, and G_{best} is the neighbourhood best position of particle i. The inertia weight w plays an important role in balancing the global search and local search. A large w facilitates a global search while a small inertia weight improves a local search. It can be a positive

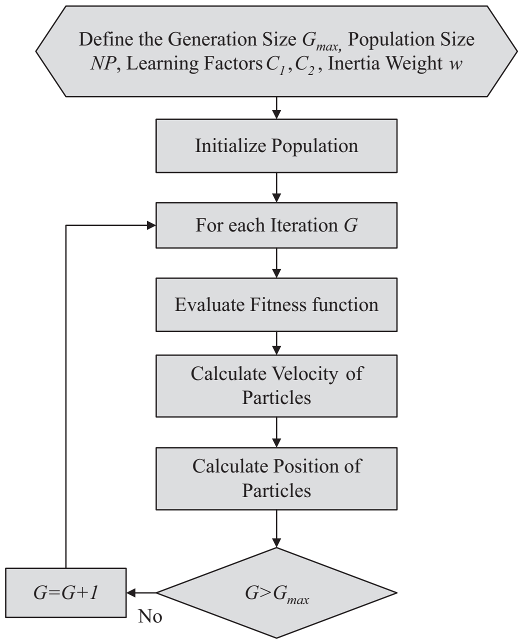

Fig. 8. The basic flow chart of PSO method.

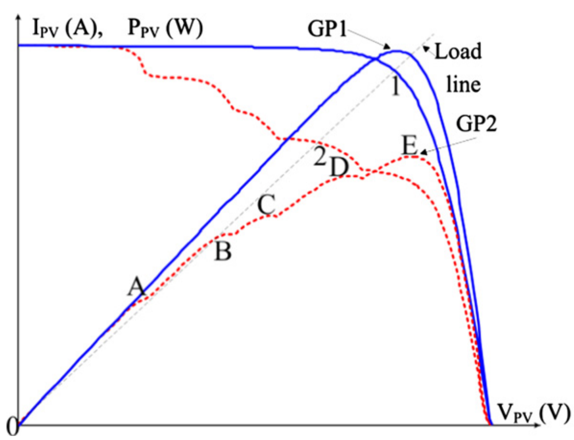

Fig. 9. The *I–V* and *P–V* curves used for evaluating the performance of various MPPT methods.

constant or a positive decreasing linear function of iteration index *j*. Fig. 8 depicts the basic flow chart of the PSO method.

Authors in [96] employ the PSO algorithm to predict the MPP of PV system. At the beginning of the evolution, the conventional PSO is applied for the global search. Once it arrives at the vicinity of the MPP, a special algorithm is triggered to quickly obtain the local optimal point. Such scheme effectively improves the speed of local search. In general, PSO is more suitably used for partial shading conditions, as shall be described in the following sections.

6.3.2. Other EA techniques

In [97], a hybrid GA-ANN MPPT is proposed. The GA is used to obtain the optimized values of array power and voltage for different insolation and temperatures conditions. The results are used for the offline training of the ANN. In a similar manner, authors in [98] propose another GA-ANN based MPPT, while in [99], GA is used to optimize the FLC based MPPT.

7. MPPT during partial shading

In this section, the performance conventional MPPT (P&O, IC, and HC) and the soft computing techniques (FLC, ANN and EA) under partial shading are reviewed.

7.1. Modified P&O

To aid the discussion, Fig. 9 is used. In this figure, the *I–V* and *P–V* curves are shown: (1) for uniform insolation (solid trace), and (2) for partially shaded condition (dotted trace). Under uniform insolation only one peak exists, i.e., GP1; the conventional P&O almost always successfully track this point. For partial shading, five peaks labelled by A–E emerge; clearly, peak E is the true MPP (GP) while the others are local. When shading occurs, the array operating point shifts from 1 to 2; the perturbation sign for the P&O reverses and control is increased. Eventually it will recognize point D as the GP, which is obviously wrong.

The above discussion highlights the limitation of the conventional P&O during partial shading and hence the need for remedial effort. In [100] a two-mode modified P&O, outlined by the flowchart in Fig. 10 is proposed. The complete algorithm is divided into two parts: (1) the main program and (2) the GP tracking routine. To avoid scanning the whole *P–V* curve, two boundary conditions (V_{min} and V_{max}) are introduced; these values are based on the voltage in the *P–V* curve of the deployed PV array. Despite this simplification, for certain shading conditions, the algorithm still needs to scan almost 80% of the *P–V* curve to ensure none of the potential peak GP is missed. As a result, the tracking speed is greatly compromised. The scanning of *P–V* curve is terminated when the highest local peak, i.e., the true GP, is found.

In another work [101], an alternative P&O using the comparison of two instantaneous power values is proposed. Mathematically, the comparison can be written as

$$\frac{P_m(t)-P_{ref}(t)}{P_m(t-1)} < \varepsilon \tag{25}$$

In (25), $[P_m(t)]$ and $[P_{ref}(t)]$ are the instantaneous measured power and instantaneous maximum power reference, respectively. Despite the good GP tracking capability, it introduces various new coefficients (which are not shown here for simplicity) that complicate the overall MPPT process. Moreover, the method is tested only on one shading condition; thus, its effectiveness is not fully validated. Authors in [102] propose a voltage sweep method to periodically change the voltage of PV array from its maximum value (near to V_{OC}) to a minimum value (near to I_{SC}). At each sampling cycle, the operating voltage and current are measured and stored in the microcontroller memory. After identifying the region of global maxima, the P&O method is executed to maintain the operation at the GP.

7.2. Modified IC

Since the global and local peaks exhibit the same derivative characteristics, i.e., ($dP/dV=0$) or ($dP/dI=0$), the original IC algorithm is unable to recognize the true MPP. Accordingly, several authors propose modified IC schemes during partial shading. For example, Kobayashi et al. [103] implement a two-stage IC method. In the first stage, the PV array is forced to operate into the neighbourhood of the GP using the values of the maximum voltage and current, i.e.,

$$R_{MP} = k\frac{V_{MP}}{I_{MP}} \tag{26}$$

where k is the correction factor, while V_{MP} and I_{MP} are approximated to be 80% of V_{OC} and 90% of I_{SC}, respectively. Subsequently,

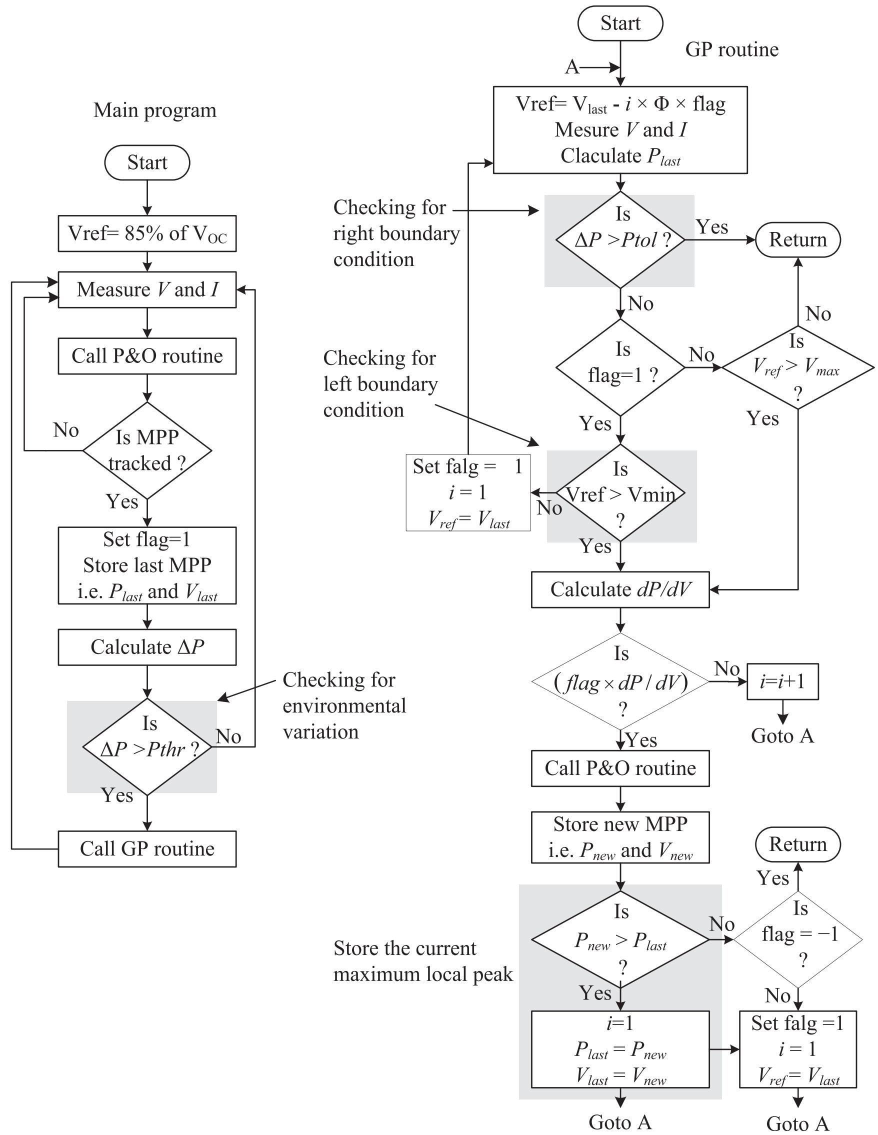

Fig. 10. Flow chart to track the GP under partial shading condition using modified P&O [100].

in the second stage, adjustment is made to move the operating point towards the GP based on the IC method. In another attempt, authors in [104] propose a linear function to track the GP under partial shading. Mathematically, it can be written as:

$$V^* = \frac{V_{grid}}{I_{out}} \times I(k) \tag{27}$$

where V_{grid} and I_{out} is the output voltage and current of the grid, respectively. The linear function is activated whenever shading condition occurs. It is detected using the following relationships:

$$V(k) - V(k-1) < V_{thr} \tag{28}$$

$$\frac{I(k) - I(k-1)}{I(k-1)} < I_{thr} \tag{29}$$

Once the PV array is subjected to partial shading, (27) shifts the operating point to the reference value (V^*). Then, the IC method is employed to track the GP. Although quite effective, the method can only be applied to a grid-connected system. Interestingly, it is observed in [104] that under rapid fluctuation of insolation, the performance of the modified IC deteriorates more rapidly compared to the conventional method.

7.3. Modified HC

Since the HC method is based on the P&O principle, the algorithm also traps at the local minima. In [105], Lei et al. proposed a duty cycle sweep method based on modified HC to cater for partial shading condition. The initial value of the duty cycle is computed using the following equation:

$$D = 1 - \sqrt{\frac{R_{MP}}{R_{Load}}} \tag{30}$$

where R_{Load} is estimated using the rating of PV array. The sweep duty cycle is carried out for the range of 0–90%. Later, the conventional HC is improved by dividing the duty cycle perturbation (Φ) by two whenever the direction of the Φ is increased. Similar to [100], this method also needs to scan over 80% of the PV curve. In another work, authors in [106] implemented a multiple-input boost converter for micro-inverters based on modified HC.

7.4. ANN and FLC in partial shading

By carefully analyzing (26), it can be deduced that the operating principle of FLC is identical to the IC; they both work on the

basis of dP/dV information. A zero value of $E(k)$ implies that the algorithm is at the MPP, i.e., $dP/dV=0$. However, in partial shading, all peaks (local and GP) exhibit the same dP/dV characteristic. Hence, FLC too cannot guarantee the true GP.

Accordingly, a modified FLC based on three stages operation is proposed in [107]. The key steps involved: (1) the scanning of P–V curve (in uniform or partial shading), (2) storing of all possible local peaks and (3) performing the perturbation and observation of the array power. Three variables, given by the following equations, are fed to the FLC inputs:

$$\Delta P = P(k) - P(k-1) \tag{31}$$

$$\Delta I = I(k) - I(k-1) \tag{32}$$

$$\Delta P_M = P_M(k) - P(k-1) \tag{33}$$

where ΔP and ΔI are the changes in array power and current in two subsequent samples, respectively. ΔP_M is the difference between the stored GP (P_M) and the currently measured power. Using these inputs, thirty-four FLC rules for the duty cycle signal (ΔD) are formulated based on the HC algorithm.

In addition, efforts have been made to combine the conventional MPPT with ANN. Syafarudin et al. [108] propose a three layer feed-forward ANN, combined with an FLC. The method is tested on different solar cell technologies, namely mono-crystalline silicon, thin-film and amorphous silicon. In another work by the same authors [109], a Fuzzy wavelet network to identify the GP of non-crystalline Si PV modules is proposed. A data set which consists of 200 input–output pairs is used to train and test the proposed ANN network. However, for both works, it is clearly recognized that obtaining the reliable training data set for partial shading is the most challenging tasks. Although shading due to towers, trees and roofs can be modelled easily, the conditions due to the uncertainty of passing clouds are extremely difficult to estimate. Since the training is carried out using predefined shading scenarios, the effectiveness of the ANN algorithm could not be guaranteed.

7.5. PSO

Since partially shaded I–V curve exhibits multimodal characteristics, PSO methods are envisaged very effective to track the GP under this condition. Miyatake et al. [110,111] utilize the conventional PSO to track the GP in a constant bus voltage application. Authors in [112] formulate an analytical expression of the objective functions based on PV current, insolation and temperature; then the conventional PSO is utilized to track the MPP. In another work, current based PSO method [113] is proposed. The current through the series inductor in boost converter is used as the reference signal to generate the PWM signals for the switching converter. Phimmasone et al. [114,115] introduce a repulsive term in the velocity equation of the PSO as follows:

$$\begin{aligned} v_i^{k+1} &= wv_i^k + c_1r_1\{P_{best\ i} - x_i^k\} + c_2r_2\{G_{best} - x_i^k\} \\ &\quad - c_3r_3\{cent^k - x_i^k\}/\{|cent^k - x_i^k| + d\}^3 \end{aligned} \tag{34}$$

where c_3 is the coefficient of repulsive particle. The function "*cent*" is the centre of all particles, described by

$$cent^k = \sum_{i=1}^{N} \frac{x_i^k}{N} \tag{35}$$

Another work by [116] propose an Adaptive Perceptive PSO (APPSO); however, due to an additional dimensional search space, the number of particles is increased significantly compared to its original counterpart [111]. This increases the computation burden, thus making real-time implementation more difficult. Further improvement is seen in [117], where the authors utilize a Bayesian fusion technique to combine PSO with IC methods, as shown in Fig. 11. The network has $N=20$ nodes represented by $[A_1, A_2, \ldots, A_N]$. They are divided into two sectors, left and right. Ten nodes $[A_1, A_2, \ldots, A_{10}]$ correspond to 10 points of the I–V curve, estimated by the PSO method. The remaining 10 nodes refer to the 10 points, estimated by the IC method. Finally, the symbol S denotes the estimated location after fusion process. Despite its effectiveness, the complexity of the method is the major constraint for implementing it using a low-cost microprocessor.

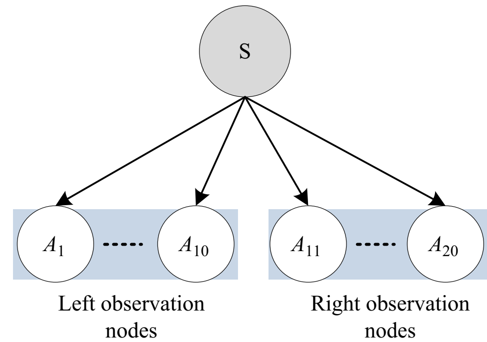

Fig. 11. Bayesian network for MPPT information fusion.

Ishaque et al. [118] adopt the PSO algorithm in the direct control structure, where the duty cycles are used as the positions of the PSO particles. The main idea is shown by flow chart in Fig. 12. If a drastic change in operating power is observed (which implies the occurrence of partial shading), the algorithm begins the search by sending duty cycles to the power converter. The information (voltage and current) obtained from these duty cycles are used to compute the P_{best} and G_{best} values. Using the velocity and position equations, the new duty cycles are computed based using the following equations:

$$\Phi_i^{k+1} = w\Phi_i^k + c_1r_1\{P_{best\ i} - x_i^k\} + c_2r_2\{G_{best} - x_i^k\} \tag{36}$$

$$d_i^{k+1} = d_i^k + \Phi_i^{k+1} \tag{37}$$

Compared with conventional HC method, this method is able to handle severe partial shading conditions with excellent dynamic tracking speed. Moreover, the steady state oscillations are found to be exceptionally low.

More recently, an improved version of [118] (proposed by the same authors) is published in [119]. The main idea is to remove the random number in the accelerations factor of the conventional PSO velocity equation. Hence it is appropriately named as deterministic the PSO (DPSO). The modification is described as follows:

$$\left.\begin{aligned} v_i^{k+1} &= wv_i^k + \{P_{best\ i} - x_i^k\} + \{G_{best} - x_i^k\} \\ &\Downarrow \\ v_i^{k+1} &= wv_i^k + \{G_{best} + P_{best\ i} - 2x_i^k\} \end{aligned}\right. \quad for\ 0 < v < V_{\max} \tag{38}$$

The maximum change in velocity ($V_{\max}$) is restricted to a particular value, which is determined based on the critical study of P–V characteristics during partial shading. The proposed method is shown to have following advantages: (1) consistent solution is achieved even for a small number of particles (2) only the inertia weight need to be tuned and (3) simpler MPPT structure compared to the conventional PSO. Despite using only three particles, it is experimentally shown that the method performs very satisfactorily under very severe shading conditions.

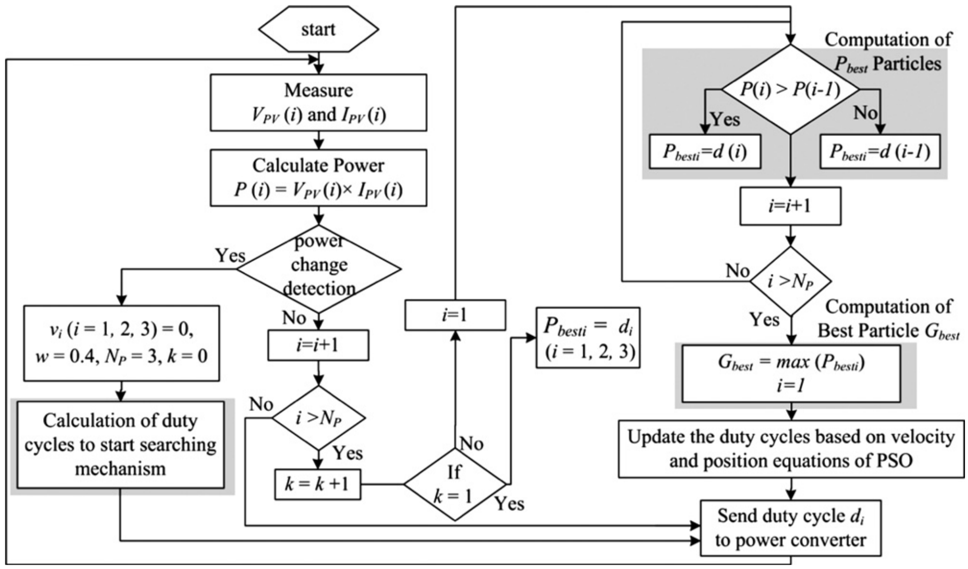

Fig. 12. Basis idea of PSO based direct control MPPT method [118].

7.6. Other EA methods

Authors in [120] propose another EA method, namely differential evolution (DE). The method is tested on three *P–V* curves, each exhibits three peaks. However, for each curve presented, the GP is on the right side, which eventually turns out to be only one shading condition. Hence, these trivial tests cannot be considered sufficient to prove the effectiveness of the method if other shading conditions occur.

Using the similar searching methodology of EA methods, another method that exploits the capability of dividing rectangles (DIRECT) algorithm is developed in [121]. It is shown that the *P–V* characteristics curve can be represented by the Lipschitz function.* The algorithm operates either in the global and local mode. Once the occurrence of partial shading is confirmed, the global mode is activated and DIRECT algorithm is applied to locate the vicinity of the GP. Thereafter, the algorithm switches to the local mode where a conventional P&O with a relatively small perturbation is employed to maintain the operating point at the GP. Once again, despite the improved tracking capability, the complexity of the method is the major issue.

8. Summary

Judging by the amount of recent work, it can be concluded that the MPPT is still a very active research area. There are rooms for improvement, particularly when dealing with partial shading conditions. For uniform insolation, there is an increasing trend in combining the conventional methods with soft computing techniques. Examples of successful schemes have been demonstrated by various works described in this paper. Such "hybrid MPPT" is quite attractive due to the availability of the vast computational power using relatively low cost microprocessors.

As for the partial shading, it appears that the EA methods are the most promising. The combination of direct duty cycle method and EA can be an interesting option to explore. The PSO, which has a very similar structure to HC has proven to be a viable option. However, there are still potential areas of concerns for EA, particularly the selection of appropriate evolutionary control parameters such as population size, mutation factor etc. This may be resolved with the assistance of other optimization technique such as ANN. There is also a need to consider the viability of EA methods when it comes to real time implementation. The way forward is to find an effective method such that the search space can be narrowed, so that the computational time is reduced. Furthermore, there are several more EA techniques, which are yet to be exploited fully. One example is the differential evolution (DE). Although it has been successfully applied in the area of PV cell modelling, it has not been used for MPPT-except for one very basic work done by [120].

* A Lipschitz function *f* is such that $|f(x)=f(y)| \leq C|x=y|$ for all *x* and *y*, where *C* is a constant independent of *x* and *y*.

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References

[1] Cacciato M, Consoli A, Attanasio R, Gennaro F. Soft-switching converter with HF transformer for grid-connected photovoltaic systems, industrial electronics. IEEE Transactions on 2010;57:1678–86.
[2] Ishaque K, Salam Z, Taheri H, Syafaruddin. Modeling and simulation of photovoltaic (PV) system during partial shading based on a two-diode model. Simulation Modelling Practice and Theory 2011;19:1613–26.
[3] R Bruendlinger, B Bletterie, M Milde, H Oldenkamp,. Maximum power point tracking performance under partially shaded PV array conditions, In: Proc. 21st EUPVSEC, Germany, 2006, p. 2157–2160.
[4] Esram T, Kimball JW, Krein PT, Chapman PL, Midya P. Dynamic maximum power point tracking of photovoltaic arrays using ripple correlation control, power electronics. IEEE Transactions on 2006;21:1282–91.
[5] Salas V, Olías E, Barrado A, Lázaro A. Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. Solar Energy Materials and Solar Cells 2006;90:1555–78.
[6] Ishaque K, Salam Z, Syafaruddin. A comprehensive MATLAB Simulink PV system simulator with partial shading capability based on two-diode model. Solar Energy 2011;85:2217–27.
[7] Hart GW, Branz HM, Cox Iii CH. Experimental tests of open-loop maximum-power-point tracking techniques for photovoltaic arrays. Solar Cells 1984;13:185–95.
[8] S Yuvarajan, X Shanguang, Photo-voltaic power converter with a simple maximum-power-point-tracker, In: circuits and systems, 2003. ISCAS '03.

proceedings of the 2003 international symposium on, 2003, p. III-399–III-402 vol. 393.
[9] N Mutoh, T Matuo, K Okada, M Sakai, Prediction-data-based maximum-power-point-tracking method for photovoltaic power generation systems, In: power electronics specialists conference, 2002. pesc 02. 2002 IEEE 33rd Annual, 2002, p. 1489–1494 vol. 1483.
[10] T Noguchi, S Togashi, R Nakamoto, Short-current pulse based adaptive maximum-power-point tracking for photovoltaic power generation system, In: industrial electronics, 2000. ISIE 2000. Proceedings of the 2000 IEEE international symposium on, 2000, p. 157–162 vol. 151.
[11] K Kobayashi, H Matsuo, Y Sekine, A novel optimum operating point tracker of the solar cell power supply system, In: power electronics specialists conference, 2004. PESC 04. 2004 IEEE 35th annual, 2004, p. 2147–2151 Vol. 2143.
[12] DJ Patterson, Electrical system design for a solar powered vehicle, In: power electronics specialists conference, 1990. PESC '90 record., 21st annual IEEE, 1990, p. 618–622.
[13] N Hyeong-Ju, L Dong-Yun, H Dong-Seok, An improved MPPT converter with current compensation method for small scaled PV-applications, In: IECON 02 [Industrial electronics society, IEEE 2002 28th annual conference of the], 2002, p. 1113–1118 vol. 1112.
[14] JHR Enslin, DB Snyman, Simplified feed-forward control of the maximum power point in PV installations, In: industrial electronics, control, instrumentation, and automation, 1992. Power electronics and motion control., Proceedings of the 1992 international conference on, 1992, p. 548–553 vol. 541.
[15] P Midya, PT Krein, RJ Turnbull, R Reppa, J Kimball, Dynamic maximum power point tracker for photovoltaic applications, In: power electronics specialists conference, 1996. PESC '96 record., 27th annual IEEE, 1996, p. 1710–1716 vol. 1712.
[16] Yan Hong L, Hamill DC. Simple maximum power point tracker for photovoltaic arrays. Electronics Letters 2000;36:997–9.
[17] L Yan Hong, DC Hamill, Synthesis, simulation and experimental verification of a maximum power point tracker from nonlinear dynamics, In: power electronics specialists conference, 2001. PESC. 2001 IEEE 32nd annual, 2001, p. 199–204 vol. 191.
[18] L Stamenic, M Greig, E Smiley, R Stojanovic, Maximum power point tracking for building integrated photovoltaic ventilation systems, In: photovoltaic specialists conference, 2000. Conference record of the twenty-eighth IEEE, 2000, p. 1517–1520.
[19] Kimball JW, Krein PT. Discrete-time ripple correlation control for maximum power point tracking, power electronics. IEEE Transactions on 2008;23:2353–62.
[20] M Bodur, M Ermis, Maximum power point tracking for low power photovoltaic solar panels, In: electrotechnical conference, 1994. Proceedings., 7th Mediterranean, 1994, p. 758–761 vol. 752.
[21] M Matsui, T Kitano, X De-hong, Y Zhong-qing, A new maximum photovoltaic power tracking control scheme based on power equilibrium at DC link, In: industry applications conference, 1999. Thirty-fourth IAS annual meeting. Conference record of the 1999 IEEE, 1999, p. 804–809 vol. 802.
[22] T Kitano, M Matsui, X De-hong, Power sensor-less MPPT control scheme utilizing power balance at DC link-system design to ensure stability and response, In: industrial electronics society, 2001. IECON '01. The 27th annual conference of the IEEE, 2001, p. 1309–1314 vol. 1302.
[23] HJ Beukes, JHR Enslin, Analysis of a new compound converter as MPPT, battery regulator and bus regulator for satellite power systems, In: power electronics specialists conference, 1993. PESC '93 record., 24th annual IEEE, 1993, p. 846–852.
[24] CR Sullivan, MJ Powers, A high-efficiency maximum power point tracker for photovoltaic arrays in a solar-powered race vehicle, In: power electronics specialists conference, 1993. PESC '93 record., 24th annual IEEE, 1993, p. 574–580.
[25] AS Kislovski, R Redl, Maximum-power-tracking using positive feedback, In: power electronics specialists conference, PESC '94 record., 25th annual IEEE, 1994, p. 1065–1068 vol. 1062.
[26] J Arias, FF Linera, J Martin-Ramos, AM Pernia, J Cambronero, A modular PV regulator based on microcontroller with maximum power point tracking, In: industry applications conference, 2004. 39th IAS annual meeting. Conference record of the 2004 IEEE, 2004, p. 1178–1184 vol. 1172.
[27] Shmilovitz D. On the control of photovoltaic maximum power point tracker via output parameters, electric power applications. IEE Proceedings 2005;152:239–48.
[28] R Bhide, SR Bhat, Modular power conditioning unit for photovoltaic applications, In: power electronics specialists conference, 1992. PESC '92 record., 23rd annual IEEE, 1992, p. 708–713 vol. 701.
[29] H Sugimoto, H Dong, A new scheme for maximum photovoltaic power tracking control, In: power conversion conference—Nagaoka 1997. Proceedings of the, 1997, p. 691–696 vol. 692.
[30] Chiang SJ, Chang KT, Yen CY. Residential photovoltaic energy storage system, industrial electronics. IEEE Transactions on 1998;45:385–94.
[31] Bleijs JAM, Gow A. Fast maximum power point control of current-fed DC-DC converter for photovoltaic arrays. Electronics Letters 2001;37:5–6.
[32] H Cong-Ling, W Jie, Z Miao, Y Jin-Ming, L Jin-Peng, Application of adaptive algorithm of solar cell battery charger, In: electric utility deregulation, restructuring and power technologies, 2004. (DRPT 2004). Proceedings of the 2004 IEEE international conference on, 2004, p. 810–813 Vol. 812.
[33] P. Ching-Tsai, C Jeng-Yue, C Chin-Peng, H Yi-Shuo, A fast maximum power point tracker for photovoltaic power systems, In: industrial electronics society, 1999. IECON '99 Proceedings. The 25th annual conference of the IEEE, 1999, p. 390–393 vol. 391.
[34] Solodovnik EV, Shengyi L, Dougal RA. Power controller design for maximum power tracking in solar installations, power electronics. IEEE Transactions on 2004;19:1295–304.
[35] PCM de Carvalho, RST Pontes, DS Oliveira, Jr, DB Riffel, RGV de Oliveira, SB Mesquita, Control method of a photovoltaic powered reverse osmosis plant without batteries based on maximum power point tracking, In: transmission and distribution conference and exposition: Latin America, 2004 IEEE/PES, 2004, p. 137–142.
[36] E.I. rtiz-Rivera, P Fang, A novel method to estimate the maximum power for a photovoltaic inverter system, In: power electronics specialists conference, 2004. PESC 04. 2004 IEEE 35th annual, 2004, p. 2065–2069 Vol. 2063.
[37] Z Miao, W Jie, Z Hui, The application of slide technology in PV maximum power point tracking system, In: intelligent control and automation, 2004. WCICA 2004. Fifth world congress on, 2004, p. 5591–5594 Vol. 5596.
[38] K Chomsuwan, P Prisuwanna, V Monyakul, Photovoltaic grid-connected inverter using two-switch buck-boost converter, In: photovoltaic specialists conference, 2002. Conference record of the twenty-ninth IEEE, 2002, p. 1527–1530.
[39] O Hashimoto, T Shimizu, G Kimura, A novel high performance utility interactive photovoltaic inverter system, In: industry applications conference, 2000. Conference record of the 2000 IEEE, 2000, p. 2255–2260 vol. 2254.
[40] Fortunato M, Giustiniani A, Petrone G, Spagnuolo G, Vitelli M. Maximum power point tracking in a one-cycle-controlled single-stage photovoltaic inverter, industrial electronics. IEEE Transactions on 2008;55:2684–93.
[41] Sang-Hoon P, Gil-Ro C, Yong-Chae J, Chung-Yuen W. Design and application for PV generation system using a soft-switching boost converter with SARC, industrial electronics. IEEE Transactions on 2010;57:515–22.
[42] H Ying-Tung, C China-Hong, Maximum power tracking for photovoltaic power system, In: industry applications conference, 2002. 37th IAS annual meeting. Conference record of the, 2002, p. 1035–1040 vol. 1032.
[43] Femia N, Petrone G, Spagnuolo G, Vitelli M. Optimization of perturb and observe maximum power point tracking method, power electronics. IEEE Transactions on 2005;20:963–73.
[44] NS D'Souza, LAC Lopes, L Xuejun, An intelligent maximum power point tracker using peak current control, In: power electronics specialists conference, 2005. PESC '05. IEEE 36th, 2005, p. 172.
[45] A Al-Amoudi, L Zhang, Optimal control of a grid-connected PV system for maximum power point tracking and unity power factor, In: power electronics and variable speed drives, 1998. Seventh international conference on (Conf. Publ. No. 456), 1998, p. 80–85.
[46] Patel H, Agarwal V. MPPT scheme for a PV-fed single-phase single-stage grid-connected inverter operating in CCM with only one current sensor, energy conversion. IEEE Transactions on 2009;24:256–63.
[47] Wasynezuk O. Dynamic behavior of a class of photovoltaic power systems, power apparatus and systems. IEEE Transactions on, PAS-102 1983:3031–7.
[48] Harada K, Zhao G. Controlled power interface between solar cells and AC source, power electronics. IEEE Transactions on 1993;8:654–62.
[49] Yeong-Chau K, Tsorng-Juu L, Jiann-Fuh C. Novel maximum-power-point-tracking controller for photovoltaic energy conversion system, Industrial Electronics. IEEE Transactions on 2001;48:594–601.
[50] GJ Yu, YS Jung, JY Choi, I Choy, JH Song, GS Kim, A novel two-mode MPPT control algorithm based on comparative study of existing algorithms, In: photovoltaic specialists conference, 2002. Conference record of the twenty-ninth IEEE, 2002, p. 1531–1534.
[51] H Koizumi, K Kurokawa, A Novel Maximum power point tracking method for PV module integrated converter, In: power electronics specialists conference, 2005. PESC '05. IEEE 36th, 2005, p. 2081–2086.
[52] W Wenkai, N Pongratananukul, Q Weihong, K Rustom, T Kasparis, I Batarseh, DSP-based multiple peak power tracking for expandable power system, In: applied power electronics conference and exposition, 2003. APEC '03. Eighteenth annual IEEE, 2003, p. 525–530 vol. 521.
[53] P Mattavelli, S Saggini, E Orietti, G Spiazzi, A simple mixed-signal MPPT circuit for photovoltaic applications, In: applied power electronics conference and exposition (APEC), 2010 twenty-fifth annual IEEE, 2010, p. 953–960.
[54] Qiang M, Mingwei S, Liying L, Guerrero JM. A. Novel improved variable step-size incremental-resistance MPPT method for PV systems, industrial electronics. IEEE Transactions on 2011;58:2427–34.
[55] L Jiyong, W Honghua, A novel stand-alone PV generation system based on variable step size INC MPPT and SVPWM control, In: power electronics and motion control conference, 2009. IPEMC '09. IEEE 6th international, 2009, p. 2155–2160.
[56] Wu L, Zhao Z, Liu J. A. single-stage three-phase grid-connected photovoltaic system with modified MPPT method and reactive power compensation, energy conversion. IEEE Transactions on 2007;22:881–6.
[57] L Jae , B HyunSu, C Bo Hyung, Advanced incremental conductance MPPT algorithm with a variable step size, In: power electronics and motion control conference, 2006EPE-PEMC 2006. 12th international, 2006, p. 603–607.
[58] T Noguchi, H Matsumoto, Maximum-power-point tracking method of photovoltaic power system using single transducer, In: industrial

electronics society, 2003. IECON '03. The 29th annual conference of the IEEE, 2003, p. 2350–2355 Vol. 2353.
[59] Koutroulis E, Kalaitzakis K, Voulgaris NC. Development of a microcontroller-based, photovoltaic maximum power point tracking control system, power electronics. IEEE Transactions on 2001;16:46–54.
[60] Kasa N, Iida T, Chen L. Flyback inverter controlled by sensorless current MPPT for photovoltaic power system, industrial electronics. IEEE Transactions on 2005;52:1145–52.
[61] Jain S, Agarwal V, Single-Stage Grid A. Connected inverter topology for solar PV systems with maximum power point tracking, power electronics. IEEE Transactions on 2007;22:1928–40.
[62] Gules, De Pellegrin Pacheco J, Hey HL, Imhoff J. A maximum power point tracking system with parallel connection for PV stand-alone applications, industrial electronics. IEEE Transactions on 2008;55:2674–83.
[63] Jung-Min K, Bong-Hwan K, Kwang-Hee N. Three-phase photovoltaic system with three-level boosting MPPT control, power electronics. IEEE Transactions on 2008;23:2319–27.
[64] C Mao-Lin, H Chih-Chiang, L Jong-Rong, Direct power control for distributed PV power system, In: power conversion conference, 2002. PCC Osaka 2002. Proceedings of the, 2002, p. 311–315 vol. 311.
[65] X Weidong, WG Dunford, A modified adaptive hill climbing MPPT method for photovoltaic power systems, In: power electronics specialists conference, 2004. PESC 04. 2004 IEEE 35th annual, 2004, p. 1957–1963 Vol. 1953.
[66] PJ Wolfs, L Tang, A single cell maximum power point tracking converter without a current sensor for high performance cehicle solar arrays, In: power electronics specialists conference, 2005. PESC '05. IEEE 36th, 2005, p. 165–171.
[67] Pandey A, Dasgupta N, Mukerjee AK. High-performance algorithms for drift avoidance and fast tracking in solar mppt system, energy conversion. IEEE Transactions on 2008;23:681–9.
[68] X Zhou, D Song, Y Ma, D Cheng, The simulation and design for MPPT of PV system based on incremental conductance method, In: information engineering (ICIE), 2010 WASE international conference on, 2010, p. 314–317.
[69] Safari A, Mekhilef S. Simulation and hardware implementation of incremental conductance MPPT with direct control method using Cuk converter, industrial electronics. IEEE Transactions on 2011;58:1154–61.
[70] P Wang, H Ding, C Diao, S Qi, An improved MPPT algorithm based on traditional incremental conductance method, In: power electronics systems and applications (PESA), 2011 4th international conference on, 2011, p. 1–4.
[71] Fangrui L, Shanxu D, Fei L, Bangyin L, Yong K. A variable step size INC MPPT method for PV systems, industrial electronics. IEEE Transactions on 2008;55:2622–8.
[72] D Menniti, A Burgio, N Sorrentino, A Pinnarelli, G Brusco, An incremental conductance method with variable step size for MPPT: design and implementation, In: electrical power quality and utilisation, 2009. EPQU 2009. 10th international conference on, 2009, p. 1–5.
[73] Ishaque K, Abdullah S, Ayob S, Salam Z. Single input fuzzy logic controller for unmanned underwater vehicle. Journal of Intelligent & Robotic Systems 2010;59:87–100.
[74] Ishaque K, Abdullah SS, Ayob SM, Salam Z. A simplified approach to design fuzzy logic controller for an underwater vehicle. Ocean Engineering 2011;38:271–84.
[75] AMA Mahmoud, HM Mashaly, SA Kandil, H El Khashab, MNF Nashed, Fuzzy logic implementation for photovoltaic maximum power tracking, In: industrial electronics society, 2000. IECON 2000. 26th annual confjerence of the IEEE, 2000, p. 735–740 vol. 731.
[76] Veerachary M, Senjyu T, Uezato K. Neural-network-based maximum-power-point tracking of coupled-inductor interleaved-boost-converter-supplied PV system using fuzzy controller, industrial electronics. IEEE Transactions on 2003;50:749–58.
[77] N Khaehintung, K Pramotung, B Tuvirat, P Sirisuk, RISC-microcontroller built-in fuzzy logic controller of maximum power point tracking for solar-powered light-flasher applications, in: Industrial Electronics Society, 2004. IECON 2004. 30th Annual Conference of IEEE, 2004, p. 2673–2678 Vol. 2673.
[78] W Chung-Yuen, K Duk-Heon, K Sei-Chan, K Won-Sam, K Hack-Sung, A new maximum power point tracker of photovoltaic arrays using fuzzy controller, In: power electronics specialists conference, PESC '94 record., 25th annual IEEE, 1994, pp. 396–403 vol. 391.
[79] MG Simoes, NN Franceschetti, M Friedhofer, A fuzzy logic based photovoltaic peak power tracking control, In: industrial electronics, 1998. Proceedings. ISIE '98. IEEE international symposium on, 1998, p. 300–305 vol. 301.
[80] Masoum MAS, Sarvi M. Design, simulation and implementation of a fuzzy-based maximum power point tracker under variable insolation and temperature conditions. Iranian Journal of Science and Technology 2005;29:6.
[81] Kottas TL, Boutalis YS, Karlis AD. New maximum power point tracker for PV arrays using fuzzy controller in close cooperation with fuzzy cognitive networks, Energy Conversion. IEEE Transactions on 2006;21:793–803.
[82] Alajmi BN, Ahmed KH, Finney SJ, Williams BW. Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in microgrid standalone photovoltaic system, power electronics. IEEE Transactions on 2011;26:1022–30.
[83] N Patcharaprakiti, S Premrudeepreechacharn, Maximum power point tracking using adaptive fuzzy logic control for grid-connected photovoltaic system, In: power engineering society winter meeting, 2002. IEEE, 2002, p. 372–377 vol. 371.
[84] TF Wu, CH Yang, YK Chen, ZR Liu, Photovoltaic inverter systems with self-tuning fuzzy control based on an experimental planning method, In: industry applications conference, 1999. Thirty-fourth IAS annual meeting. Conference record of the 1999 IEEE, 1999, p. 1887–1894 vol. 1883.
[85] I Purnama, L Yu-Kang, C Huang-Jen, A fuzzy control maximum power point tracking photovoltaic system, In: fuzzy systems (FUZZ), 2011 IEEE international conference on, 2011, p. 2432–2439.
[86] Byung-Jae C, Seong-Woo K, Byung Kook K. Design and stability analysis of single-input fuzzy logic controller, systems, man, and cybernetics, Part B: Cybernetics. IEEE Transactions on 2000;30:303–9.
[87] Syafaruddin E, Karatepe T. Hiyama, Polar coordinated fuzzy controller based real-time maximumpower point control of photovoltaic system. Renewable Energy 2009;34:10.
[88] Veerachary M, Yadaiah N. ANN based peak power tracking for PV supplied DC motors. Solar Energy 2000;69:343–50.
[89] AMZ Alabedin, EF El-Saadany, MMA Salama, Maximum power point tracking for Photovoltaic systems using fuzzy logic and artificial neural networks, In: power and energy society general meeting, 2011 IEEE, 2011, p. 1–9.
[90] X Jinbang, S Anwen, Y Cheng, R Wenpei, Y Xuan, ANN based on IncCond algorithm for MPP tracker, In: bio-inspired computing: theories and applications (BIC-TA), 2011 sixth international conference on, 2011, p. 129–134.
[91] MA Islam, MA Kabir, Neural network based maximum power point tracking of photovoltaic arrays, In: TENCON 2011–2011 IEEE region 10 conference, 2011, p. 79–82.
[92] Ishaque K, Salam Z. An improved modeling method to determine the model parameters of photovoltaic (PV) modules using differential evolution (DE). Solar Energy 2011;85:2349–59.
[93] Ishaque K, Salam Z, Taheri H, Shamsudin A. A critical evaluation of EA computational methods for Photovoltaic cell parameter extraction based on two diode model. Solar Energy 2011;85:1768–79.
[94] K Ishaque, Z Salam, A Shamsudin, Application of particle swarm optimization for maximum power point tracking of PV system with direct control method, In: 37th annual conference on IEEE industrial electronics society, 2011, p. 1214–1219.
[95] R Eberhart, J Kennedy, A new optimizer using particle swarm theory, In: micro machine and human science, 1995. MHS '95., Proceedings of the sixth international symposium on, 1995, p. 39–43.
[96] F Qiang, T Nan, A. Complex-method-based PSO algorithm for the maximum power point tracking in photovoltaic system, In: information technology and computer science (ITCS), 2010 second international conference on, 2010, p. 134–137.
[97] R Ramaprabha, V Gothandaraman, K Kanimozhi, R Divya, BL Mathur, Maximum power point tracking using GA-optimized artificial neural network for Solar PV system, In: electrical energy systems (ICEES), 2011 1st international conference on, 2011, p. 264–268.
[98] J Long, Z Chen, Research on the MPPT algorithms of photovoltaic system based on PV neural network, In: control and decision conference (CCDC), 2011 Chinese, 2011, p. 1851–1854.
[99] Messai A, Mellit A, Guessoum A, Kalogirou SA. Maximum power point tracking using a GA optimized fuzzy logic controller and its FPGA implementation. Solar Energy 2011;85:265–77.
[100] Patel H, Agarwal V. Maximum power point tracking scheme for PV systems operating under partially shaded conditions, industrial electronics. IEEE Transactions on 2008;55:1689–98.
[101] Carannante G, Fraddanno C, Pagano M, Piegari L. Experimental performance of MPPT algorithm for photovoltaic sources subject to inhomogeneous insolation. IEEE Transaction on Industrial Electronics 2009;56:7.
[102] E Koutroulis, F Blaabjerg, A New Technique for tracking the global maximum power point of PV arrays operating under partial-shading conditions, IEEE Journal of Photovoltaics, in press (2012).
[103] Kobayashi K, Takano I, Sawada Y. A study of a two stage maximum power point tracking control of a photovoltaic system under partially shaded insolation conditions. Solar Energy Materials and Solar Cells 2006;90:2975–88.
[104] Young-Hyok J, Doo-Yong J, Jun-Gu K, Jae-Hyung K, Tae-Won L, Chung-Yuen W. A. real maximum power point tracking method for mismatching compensation in PV array under partially shaded conditions, power electronics. IEEE Transactions on 2011;26:1001–9.
[105] M Lie, S Yaojie, L Yandan, B Zhifeng, T Liqin, S Jieqiong, A. high performance MPPT control method, In: materials for renewable energy & environment (ICMREE), 2011, p. 195–199.
[106] SV Dhople, JL Ehlmann, A Davoudi, PL Chapman, Multiple-input boost converter to minimize power losses due to partial shading in photovoltaic modules, In: energy conversion congress and exposition (ECCE), 2010, p. 2633–2636.
[107] BN Alajmi, KH Ahmed, SJ Finney, BW Williams, A maximum power point tracking technique for partially shaded photovoltaic systems in microgrids, industrial electronics, IEEE transactions on, in press (2011).
[108] Syafaruddin E, Karatepe T. Hiyama, artificial neural network-polar coordinated fuzzy controller based maximum power point tracking control under partially shaded conditions. IET Renewable Power Generation 2008;3:15.
[109] Syafaruddin E, Karatepe T. Hiyama, Fuzzy wavelet network identification of optimum operating point of non-crystalline silicon solar cells, Computers &amp. Mathematics with Applications 2012;63:68–82.
[110] M Miyatake, T Inada, I Hiratsuka, Z Hongyan, H Otsuka, M Nakano, Control characteristics of a fibonacci-search-based maximum power point tracker

when a photovoltaic array is partially shaded, In: power electronics and motion control conference, 2004. IPEMC 2004. The 4th international, 2004, p. 816–821 Vol. 812.
[111] M Miyatake, F Toriumi, T Endo, N Fujii, A Novel maximum power point tracker controlling several converters connected to photovoltaic arrays with particle swarm optimization technique, In: power electronics and applications, 2007 European conference on, 2007, p. 1–10.
[112] Y Liu, D Xia, Z He, MPPT of a PV system based on the particle swarm optimization In: electric utility deregulation and restructuring and power technologies (DRPT), 2011, p. 1094–1096.
[113] K Ishaque, Z Salam, H Taheri, A Shamsudin, Maximum power point tracking for PV system under partial shading condition via particle swarm optimization, In: applied power electronics colloquium (IAPEC), 2011 IEEE, 2011, p. 5–9.
[114] V Phimmasone, T Endo, Y Kondo, M Miyatake, Improvement of the maximum power point tracker for photovoltaic generators with particle swarm optimization technique by adding repulsive force among agents, In: electrical machines and systems, 2009, p. 1–6.
[115] V Phimmasone, Y Kondo, T Kamejima, M Miyatake, Evaluation of extracted energy from PV with PSO-based MPPT against various types of solar irradiation changes, In: electrical machines and systems (ICEMS), 2010, p. 487–492.
[116] Roy Chowdhury S, Saha H. Maximum power point tracking of partially shaded solar photovoltaic arrays. Solar Energy Materials and Solar Cells 2010;94:1441–7.
[117] F Keyrouz, S Georges, Efficient multidimensional maximum power point tracking using bayesian fusion, In: electric power and energy conversion systems (EPECS), 2011, p. 1–5.
[118] K Ishaque, Z Salam, M Amjad, S Mekhilef,. An improved particle swarm optimization (PSO)-based MPPT for PV with reduced steady state oscillation, IEEE transactions on power electronics, 27 (2012) 3627–3638.
[119] K Ishaque, Z Salam, A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition, IEEE Transaction on Industrial Electronics, In press (2012).
[120] H Taheri, K Ishaque, Z Salam, A. Novel maximum power point tracking control of photovoltaic system under partial and rapidly fluctuating shadow conditions using differential evolution, In: IEEE symposium on industrial electronics & applications (ISIEA), 2010, p. 82–87.
[121] Tat Luat N, Kay-Soon L. A global maximum power point tracking scheme employing DIRECT search algorithm for photovoltaic systems, industrial electronics. IEEE Transactions on 2010;57:3456–67.